NAVAL HEALTH RESEARCH CENTER

THERMOREGULATORY CONSEQUENCES OF

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Summary

Problem

Military personnel are sometimes required to do work in hot environments while encapsulated in chemical protective (CP) clothing. Physical activity in this environment can pose a serious health hazard, resulting in illness or injury ranging from muscle cramps and nausea to collapse and even death. To reduce adverse consequences, safety standards defining tolerance times have been established. In addition, microclimate cooling devices have been used to negate the effects of hot and noxious environments. Safety standards and microclimate cooling devices have been developed for use when lower body exercise (LBE) is required. Although most military tasks require the use of the lower body, sometimes upper body exercise (UBE) is required. Since safety standards and microclimate cooling have been developed and tested with LBE and not with UBE, it is necessary to determine if heat strain is affected by mode of exercise. Physiological indicators of heat strain, such as an elevation in heart rate, have been shown to be greater with UBE than with LBE. It is uncertain how differences in physiological responses to UBE compared with responses to LBE would alter the effectiveness of microclimate cooling or the tolerance times defined by safety standards.

Objective

The purpose of this study was to determine if mode of exercise affects tolerance time in an extremely hot environment when normal avenues of heat loss are restricted by CP clothing. In addition, this study was designed to determine if cooling requirement and heat transfer to a liquid-based cooling system were different between UBE and LBE.

Approach

Eight subjects alternated 10-min rest with 20-min moderate exercise for 120 min in a hot environment (49°C, 20% relative humidity). The subjects completed four tests consisting of arm cranking with no cooling (UBE-NC), arm cranking with cooling (UBE-C), treadmill walking with no cooling (LBE-NC), and treadmill walking with cooling (LBE-C). Indices of heat strain (e.g., heart rate [HR], core temperature [T_{re}], and sweat rate [SR]) and heat transfer (Q) were compared between exercise modes within cooling conditions.

Results

For NC trials, no subject was able to endure 120 min of heat exposure. Tolerance time was not significantly greater during LBE-NC (56 ± 13 min) than tolerance time during UBE-NC (51 ± 12 min). In general, indices of heat strain were similar between the LBE and UBE when no cooling was provided. When cooling was provided, SR and T_{re} were similar between exercise modes, but HR was significantly higher for UBE-C (109 ± 19 beats·min^{-1}) than for LBE-C (96 ± 10 beats·min^{-1}).

Conclusion

Heat strain indices did not differ between the UBE and LBE trials in both the NC and C conditions. UBE elicited a greater HR response than LBE, but this difference was reduced in the NC condition. Heat strain appears to be related to metabolic rate rather than to region of muscle mass employed. HR, on the other hand, did differ between exercise modes. Subjective determinations of cooling requirements did not differ between UBE and LBE. Heat transfer to the cooling system was slightly greater during LBE than during UBE, possibly due to the lower efficiency in performance of LBE. Under these conditions, heat transfer and heat strain appear to be related to metabolic heat production rather than to region of muscular activity. Thus, safety standards and cooling devices currently used by the military may offer equivalent protection against heat injury when either LBE or UBE is required.

Introduction

Military personnel sometimes are required to work in hot environments while encapsulated in chemical protective (CP) clothing. Physical activity in this environment can pose a serious health hazard, resulting in illness or injury ranging from muscle cramps and nausea to collapse and even death. To minimize adverse consequences, safety standards defining tolerance times have been established (U.S. Navy, 1988). In addition, microclimate cooling devices have been used to negate the effects of hot and noxious environments. Safety standards and microclimate cooling devices have been developed for use when lower body exercise (LBE) is required. Although most military tasks require the use of the lower body, sometimes upper body exercise (UBE) is required. Since safety standards and microclimate cooling have been developed and tested with LBE and not with UBE, it is necessary to determine if heat strain is affected by mode of exercise. Physiological indicators of heat strain, such as an elevation in heart rate, have been shown to be greater with UBE than with LBE. It is uncertain how differences in physiological responses to UBE compared with responses to LBE would alter the effectiveness of microclimate cooling or the tolerance times.

Cardiorespiratory Physiology With Upper Body Exercise

At any given submaximal oxygen uptake ($\dot{V}O_2$) or power output (PO), exercise involving the smaller muscle mass of the upper body imposes a greater cardiovascular demand than exercise involving the larger muscle mass of the lower body. At an absolute PO, compared with LBE, UBE is associated with higher heart rate (HR) (Louhevaara et al., 1990; Toner et al., 1983), lower stroke volume (SV) (Bevegard et al., 1966), higher systolic and diastolic blood pressure (Bevegard et al., 1966; Miles et al., 1983), greater mean aortic pressure (Bevegard et al., 1966), higher total peripheral resistance (Astrand et al., 1965; Bevegard et al., 1966), and greater plasma volume (PV) loss (Miles et al., 1983; Pimental et al., 1984). At any given submaximal $\dot{V}O_2$, UBE elicits a greater respiratory response than LBE, including a higher minute ventilation ($\dot{V}_E$) (Bevegard et al., 1966; Pimental et al., 1984; Sawka et al., 1982; Toner et al., 1983). The higher $\dot{V}_E$ with UBE has been attributed to an increase in breathing rate (f) and tidal volume (TV) (Bevegard et al., 1966).

The previously noted differences between UBE and LBE may account for the greater cardiovascular strain induced by UBE. For instance, it has been demonstrated that the mechanical efficiency of UBE is 2% to 5% lower than LBE (Bevegard et al., 1966; Sawka et al., 1982; Toner et al., 1983). Therefore, when UBE is performed at the same PO as LBE, UBE

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requires a slightly greater $\dot{V}O_2$. The difference in efficiency has been attributed to smaller muscle mass utilized and to the greater isometric exercise component required with UBE than with LBE (Astrand et al., 1965; Bevegard et al., 1966; Sawka et al., 1982). Regardless of the mode of exercise, a linear relationship exists between cardiac output and $\dot{V}O_2$ (Miles et al., 1984; Freyschuss & Strandell, 1967; Stenberg et al., 1967); therefore, when UBE and LBE are performed at the same PO, UBE requires a greater cardiac output. This greater cardiac output requirement must be maintained despite the lower SV associated with UBE. It has been shown that SV during seated UBE is 10% to 18% lower than during seated LBE when exercises were matched for $\dot{V}O_2$ (Bevegard et al., 1966) or PO (Stenberg et al., 1967). The diminished SV during UBE has been attributed to a decrease in venous return due to elevated thoracic pressure and limited muscle pumping.

To provide a better understanding of the cardiovascular responses to UBE, studies have been conducted in which body position was varied. In those studies, SV was found to be greater when UBE was performed in a supine rather than in a seated position (Bevegard et al., 1966; Stenberg et al., 1967). When supine UBE and LBE were matched for $\dot{V}O_2$, SV was not significantly different between the two modes of exercise (Bevegard et al., 1966); however when supine UBE and LBE were matched for PO, SV was lower during UBE than during LBE (Stenberg et al., 1967). Although total peripheral resistance, mean arterial pressure, and mean aortic pressure were lower when UBE was performed in a supine position than in a sitting position, they were higher than during LBE performed in either position (Bevegard et al., 1966; Stenberg et al., 1967). The higher vascular pressures, evidence of greater vasoconstrictor tone, may facilitate venous return and serve to increase SV during UBE; however, an increase in vasoconstrictor tone is an inadequate compensatory mechanism to maintain SV at levels seen during seated LBE (Bevegard et al., 1966; Stenberg et al., 1967). During UBE, HR was lower when exercise was performed in a supine rather than in a seated position; however, HR during supine UBE was higher than HR during either seated or supine LBE (Bevegard et al., 1966; Stenberg et al., 1967). Therefore, vasoconstrictor tone increased to compensate for the reduced venous return during UBE. As venous return decreased from supine to seated UBE, these compensatory responses (i.e., HR, total peripheral resistance, and mean arterial pressure) increased accordingly.

Thermoregulation With UBE

At a given PO or $\dot{V}O_2$, when compared with LBE, upright UBE places a greater stress on the cardiovascular system, primarily manifested as a higher HR due to a reduced SV. This fact has serious thermoregulatory consequences when heat stress is combined with UBE. When

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exercise is performed in a hot environment, physiological adjustments occur that enhance heat loss. These adjustments include an increase in cutaneous blood flow and an increase in sweat rate (SR). Because an increase in cutaneous blood flow reduces central blood volume and an increase in SR reduces PV, these thermoregulatory responses diminish venous return. Thus, a circulatory dilemma arises when exercise is performed in the heat. Cardiac output must be sufficient to meet both the metabolic needs of the active tissue and the thermoregulatory needs of the body, despite a reduction in SV and a limited ability to increase HR. It has long been known that over time SV decreases when LBE is performed in a hot environment, and that HR increases when SV falls in an attempt to maintain cardiac output (Rowell et al., 1966). This compensatory increase in HR has been termed "cardiac upward drift." Cardiac upward drift can also occur with UBE in the heat (Hopman et al., 1993). Since at any absolute PO in a thermoneutral environment, HR is higher, SV is lower, and PV loss is greater during UBE than during LBE (Miles et al., 1983; Pimental et al., 1984), the question arises whether the cardiovascular system can provide adequate cardiac output to support both thermoregulatory and metabolic requirements during UBE when heat stress is introduced.

Little attention has been given to the exercise mode-related differences in thermoregulation. Research findings show that UBE and LBE performed at the same $\dot{V}O_2$ or PO resulted in similar core temperature, SR, and mean skin temperature ($\bar{T}_{sk}$) responses when exercise was performed in a thermoneutral environment (Sawka et al., 1984a; Sawka et al., 1984b) or in a warm environment (33°C to 35°C) (Pivarnik et al., 1988; Sawka et al., 1984a). Review of the literature yielded only one study that reported exercise mode-related differences in cardiovascular responses when heat stress was presented. Pivarnik et al. (1988) showed that HR was higher during UBE in a warm environment than in a thermoneutral environment and was higher than LBE in either a warm or thermoneutral environment. Clearly, the scarcity of information regarding the thermoregulatory consequences of UBE and the knowledge that UBE imposes a greater cardiovascular demand than LBE indicates that further investigation of the subject is warranted.

Heat Exchange With UBE

Heat strain indices, such as SR and rectal temperature (T_{re}), are related to metabolic rate and not the region of muscle mass employed. However, local heat exchange may differ with mode of exercise. For example, some physiological responses that may influence local heat exchange, such as regional T_{sk}, differ with mode of exercise. It has been shown that UBE elicits higher T_{sk} on the arm (Rintamaki et al., 1992); whereas LBE elicits higher T_{sk} on the calf (Rintamaki et al., 1992; Sawka et al., 1984a). A difference in regional T_{sk} suggests there may be

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regional differences in radiant and conductive (R + C) heat transfer. In fact, in a warm-dry environment, dry heat loss is greater over the upper torso during UBE than during LBE, and greater over the leg during LBE than during UBE (Sawka et al., 1984a). However, Sawka et al. (1984a) also found no exercise mode-related difference in dry heat loss over the arm. In this same study, evaporative heat loss was found to be greater over active tissue only during LBE. Thus, it may be concluded that local heat exchange is related to region of muscular activity, and whole body heat exchange is a function of metabolic rate.

The purpose of this study was to determine if mode of exercise would affect tolerance time in an extremely hot environment if normal avenues of heat loss were restricted by chemical protective clothing. In addition, this study was designed to determine if cooling requirements and heat transfer to a cooling system differ between UBE and LBE.

Methods

Experimental Design

The subjects participated in four 120-min experimental trials in which moderate exercise ($\dot{V}O_2 \approx 1.2$ L/min) was performed in a hot-dry environment (49°C, 20% relative humidity [RH]). The subjects completed initial physical characteristic testing and testing under the following conditions: arm cranking with cooling (UBE-C) and without cooling (UBE-NC), and treadmill walking with cooling (LBE-C) and without cooling (LBE-NC). To minimize treatment interaction, each of the four experimental trials were conducted in a counterbalanced fashion with at least 3 days between trials for each subject.

Initial Test Protocol

An initial test day consisted of anthropometric measurements, two peak oxygen uptake tests ($\dot{V}O_{2peak}$), one on an arm crank ergometer and one on a treadmill, and a bout of submaximal steady state exercise on each device. The maximal effort tests were separated by at least 30 min and were administered in a counterbalanced fashion. The submaximal steady state tests were approximately 30 min after the last $\dot{V}O_{2peak}$ test.

Anthropometric measurements. Height and body weight were measured on a standard physician's scale. Skinfold thicknesses were measured with a Harpenden caliper (British Indicator. LTD; St Albens, Herts, England).

Procedure for UBE $\dot{V}O_{2peak}$ test. A mechanically braked bicycle ergometer (Monarch; Varberg,

Sweden) with handgrips in place of the pedals was used as an arm crank. This ergometer provided a visual display of cranking frequency. The ergometer was able to alter resistance on the flywheel with fluctuations in revolution rate to maintain a specified PO. The ergometer was mounted on a stable platform, and an adjustable stand was used to position the subject so the crank was at shoulder height and the extended arm was slightly flexed. The arm crank exercise was performed in a standing position without body restraints. A continuous protocol with incremental loading at a pedal rate of 70 rpm was used to elicit a maximal effort. The test protocol began with three continuous 2-min warmup stages at POs of 25, 50, and 75 W. After the warmup, a 3- to 5-min rest period ensued during which the subject was encouraged to stretch. The first stage of the maximal effort test began with a PO of 75 W; thereafter, the PO was increased by 25 W every 2 min until one of the criteria for termination was achieved.

Procedure for LBE $\dot{V}O_{2peak}$ test. This test was conducted on a motorized treadmill using an incremental load protocol. The protocol began with three consecutive 2-min warm-up stages at 2, 3, and 4 mph, all at 3% grade. The maximal effort test began at a 0% grade and at a speed that was 1 min/mile slower than the speed which the subject attained for their previous physical readiness test (i.e., pace for a 1.5 mile timed run). During each of the first three 2-min stages, running speed increased 30 s·mile⁻¹; thereafter, the treadmill grade was increased 2% every 2 min until one of the criteria for termination was achieved.

Criteria for termination of $\dot{V}O_{2peak}$ tests. Criteria for test termination included volitional exhaustion, or no increase in HR or $\dot{V}O_2$ with an increase in PO.

Respiratory measurements during $\dot{V}O_{2peak}$ tests. During the $\dot{V}O_{2peak}$ tests, $\dot{V}O_2$ and $\dot{V}_E$ were continuously measured and averaged over 15-s intervals by an automated open-circuit spirometry system (Vacumed; Ventura, CA). On those occasions when the automated system failed, expired air was collected in a gas impermeable bag and analyzed for percent oxygen (S-3A/1, Ametek, Inc.; Pittsburgh, PA), percent carbon dioxide (CD-3A, Ametek, Inc.; Pittsburgh, PA), and volume (Tissot Spirometer, Collins, Inc; Braintree, MA). These variables were used to calculate $\dot{V}O_2$ and $\dot{V}_E$. $\dot{V}O_{2peak}$ was defined as the highest values attained over a 45-s period during the $\dot{V}O_{2peak}$ tests.

Heart rate measurement during $\dot{V}O_{2peak}$ tests. HR during the $\dot{V}O_{2peak}$ tests was recorded as a 15-s average by a telemetry system (Polar Heart Watch; Stamford, CT). Peak HR was defined as the highest values attained over a 45-s period during the maximal effort test.

Steady state tests. While instrumented and equipped as in the experimental test, the subjects performed 10 min of exercise at a submaximal PO. The initial PO selected was determined from the $\dot{V}O_2$ obtained during the warmup stages of the maximal effort tests. If the initial PO elicited the target $\dot{V}O_2$ of 1.2 L/min for 3 min, the steady state bout was terminated. If the target $\dot{V}O_2$ was not achieved, the PO was manipulated every 5 min to 7 min until a $\dot{V}O_2$ of 1.2 L/min was achieved, maintained for 3 min, and the corresponding PO identified. Once the appropriate PO was identified for one mode of exercise, steady state exercise for the alternate exercise mode commenced.

Pretest Instructions

To ensure adequate hydration, the subjects were instructed to avoid heat exposure, alcohol consumption, and strenuous exercise for 24 hr prior to each trial. In addition, the subjects were instructed to supplement normal hydration by drinking at least 24 ounces of noncaffeinated fluid 12 hr before each trial.

Each test day, the volunteer reported to the laboratory at the same time of day. Before testing, urine specific gravity was assessed by refractometry to ensure adequate hydration. Euhydration was defined as urine specific gravity of < 1.028.

Liquid Cooling System

A calorimeter was used to measure dry heat exchange. The calorimeter consisted of a tube suit worn next to the body, a water bath, thermistors, and flow meters. The tube suit was an elastic garment embedded with a network of Tygon tubing (Norton Performance Plastics; Akron, OH) (inner diameter = 1.66 mm; outer diameter = 3.22 mm). A total of 157 m of tubing were distributed over six separate body regions: head/neck (16 m), arms (29 m), upper torso (24 m), lower torso (22 m), thighs (29 m), and lower legs (37 m). Water circulated through the tube suit from a temperature-controlled 30 L reservoir (Model No. HX-150; Neslab; Portsmouth, NH). The water velocity was kept constant at 3.6 L/min. Inlet water temperature (T_{wi}) was manipulated throughout the test to elicit a subjective thermal sensation of "slightly cool" on a thermal sensation (TS) scale (see Figure 1). T_{wi} and outlet water temperatures (T_{wo}) were measured with precision thermistors accurate to ± 0.002°C (Model No. SP034-47; Yellow Springs Instruments, Inc.; Yellow Springs, OH). The thermistors were characterized by the manufacturer: for each thermistor, resistance at three temperatures (i.e., 0°C, 25°C, and 40°C) was measured and then a resistance-temperature curve was derived using an equation for nonideal semiconductors (Steinhardt & Hart, 1968). The mass water flow ($\dot{m}_w$) was measured with a turbine flowmeter calibrated by the manufacturer (3 points) (EG&G Technology; Phoenix,

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AZ). The accuracy of the flowmeter was assessed in our laboratory by weighing the water collected from the water loop during a 10-min period. The flowmeter was determined to have an error rate of ± 0.01%. Both water flow and temperature measurement were averaged and recorded over 2-min intervals.

Bioinstrumentation

Before each trial, the volunteers were instrumented with eight skin temperature thermistors (Model No. 409; Yellow Springs Instruments, Inc.; Yellow Springs, OH) placed on the left side of the body at the cheek (ch), shoulder (sh), forearm (fa), hand (ha), abdomen (ab), thigh (th), calf (ca), and foot (fo). T_{re} was measured using a disposable thermistor probe (Sheridan; Argyle, NY) inserted to a depth of 15 cm beyond the anal sphincter. The rectal and skin thermistors were connected to a digital analog recorder (Science Electronics, Inc.; Miamisburg, OH) for continuous visual monitoring and data recording every minute. HR during the tests was recorded as a 60-s average by a telemetry system (Polar Heart Watch; Stamford, CT).

After temperature and HR monitors were in place, the volunteers donned a clothing ensemble that consisted of the following layers: (1) shorts, underwear, and socks; (2) tube suit (i.e., the portion of the calorimeter worn next to the body); (3) coveralls and athletic shoes; (4) CP ensemble (i.e., bibbed trousers, hooded jacket, gas mask [filter removed], rubber cowl, butyl rubber gloves, and rubber boots). The clothing ensemble, tube suit, and bioinstrumentation weighed 14 kg. During the NC conditions, the tube suit was emptied of water.

Experimental Procedures

After bioinstrumentation was completed, the subject remained seated quietly outside the chamber for 12 min. In the cooling conditions, water was circulated through the calorimeter during this rest period. Upon entering the chamber, the volunteers either walked on a treadmill or performed the arm crank exercise. The test protocol consisted of four alternating periods of 20-min exercise and 10-min rest. The maximum heat exposure time was set at 120 min. The PO on the arm ergometer and speed on the treadmill (maintained at a 3% grade) were altered to elicit an $\dot{V}O_2$ of ≈1.2 L·min⁻¹. The test ended when the subject reached any of the following criteria for termination:

1. T_{re} of 39.5°C
2. 85% of ergometer-specific peak HR for 20 min
3. HR of ≥ 180 beats·min⁻¹ for 5 min
4. HR at rest of ≥ 160 beats·min⁻¹ for 5 min

5. Sweat cessation, nausea, vomiting, retching, syncope, cramps, dizziness, disorientation

6. Subject requested to stop

7. 120 min of heat exposure

At approximately minute 15 of every exercise period, the subject's $\dot{V}O_2$ was measured. Expired air was obtained through an adapter on the outport of the gas mask. During tests, $\dot{V}O_2$ and $\dot{V}_E$ were continuously measured and averaged over 60-s intervals by an automated open-circuit spirometry system (Vacumed; Ventura, CA). Every 4 min throughout the trial, the volunteer's rating of perceived exertion (RPE) and TS were recorded. The RPE scale (Borg, 1982) is based on scoring from 6 to 20. The TS scale used was slightly modified from Gagge et al. (1967) (see Figure 1).

+4 Very Hot

+3 Hot

+2 Warm

+1 Slightly Warm

 0 Neutral

−1 Slight Cool

−2 Cool

−3 Cold

−4 Very Cold

Figure 1. Thermal Sensation Scale

Calculations

The rate of heat removal was calculated using the $\dot{m}_w$ through the calorimeter and using the change in water temperature from the inlet to the outlet of the tube suit. Heat transfer rate ($\dot{Q}$) was calculated:

$$\dot{Q} = \dot{m}_w * c_w * (\Delta T_w)$$

where $\dot{Q}$ = rate of heat transfer to the cooling system (W), $\dot{m}_w$ = mass flow of water, c_w = specific heat of water, ΔT_w = change in water temperature from the inlet to the outlet side of the tube suit (Halliday et al., 1988).

Total body SR was calculated from change in nude body weight corrected for urine output and fluids consumed. Evaporative sweat rate (ESR) was calculated from a change in clothed weight corrected for urine output and fluids consumed.

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$\bar{T}_{sk}$ was calculated from the formula: $(0.07 \cdot T_{ch}) + (0.175 \cdot T_{sh}) + (0.175 \cdot T_{ab}) + (0.14 \cdot T_{fa}) + (0.05 \cdot T_{ha}) + (0.19 \cdot T_{th}) + (0.13 \cdot T_{ca}) + (0.07 \cdot T_{fo})$ (Hardy & DuBois, 1938).

Body composition was assessed using four skinfold measurements. Body density was calculated using the Durnin & Womersley (1974) equations. Percent body fat (%Fat) was calculated using an equation derived by Siri (1956). Body surface area (A_D) was calculated according to DuBois & DuBois (1915) using height and weight.

Statistical Analysis

An analysis of variance with repeated measures on the independent variables of exercise time and exercise mode was used to analyze the dependent variables of $\bar{T}_{sk}$, T_{re}, HR, RPE, $\dot{V}O_2$, $\dot{V}_E$, and $\dot{Q}$. In the NC conditions, all of the tests terminated prior to 120 min and all at different times. Therefore, the time intervals examined were minutes 10, 20, and 40. All subjects in the NC conditions completed at least 40 min of the test. In the C conditions, time intervals examined were minutes 20, 50, 80, and 110. C sampling periods were at the end of each exercise bout. $\bar{T}_{sk}$, T_{re}, and HR were recorded as a mean over 3 min. Tolerance time, SR, ESR, final $\dot{V}_E$, final HR, and final T_{re} were compared between the exercise modes using analysis of variance with repeated measures. When significant differences were found, Tukey's test of critical difference was used for post hoc analysis. In all statistical tests, a value of $p < 0.05$ was accepted as significant. All values are expressed as mean ± standard deviation (SD).

Results

Subject Characteristics

Eight male military personnel, after providing written informed consent, served as subjects for this study. The physical characteristics of the subjects are shown in Table 1 and results from the maximal effort tests are shown in Table 2.

Table 1. Physical Characteristics (mean ± SD) of the subjects.

Age (years)	Height (cm)	Weight (Kg)	A_D (m^2)	%Fat
28 ± 3	175.2 ± 3.0	72.0 ± 6.6	1.88 ± 0.09	17 ± 5

Table 2. Peak values (mean ± SD) for $\dot{V}O_2$, HR, and PO.

	LBE	UBE
$\dot{V}O_{2peak}$ (mL·kg^{-1}·min^{-1})	62.7 ± 8.3	49.6 ± 10.0
$\dot{V}O_{2peak}$ (L·min^{-1})	4.5 ± 0.5	3.5 ± 0.6
Peak HR (beats·min^{-1})	189 ± 7	176 ± 16
Peak PO (W)	1722 ± 404	182 ± 21

<u>Tolerance Time</u>

No subject was able to complete 120 min of heat exposure in the NC conditions. The average tolerance time for UBE-NC (51 ± 12 min) was less, but not significantly different, than for LBE-NC (56 ± 13 min) tests. All of the volunteers completed the 120-min test during the C conditions.

<u>Body Temperatures</u>

T_{re} at termination for UBE-NC (38.2 ± 0.4°C) and for LBE-NC (38.7 ± 0.4°C) were not different nor was T_{re} at termination for UBE-C (37.2 ± 0.2°C) and for LBE-C (37.4 ± 0.3°C). T_{re} with time is displayed in Figure 2. T_{re} increased over time in the NC ($p < 0.001$) and C ($p < 0.05$) trials. However, no significant exercise-mode effect was revealed for T_{re} in either NC or C conditions.
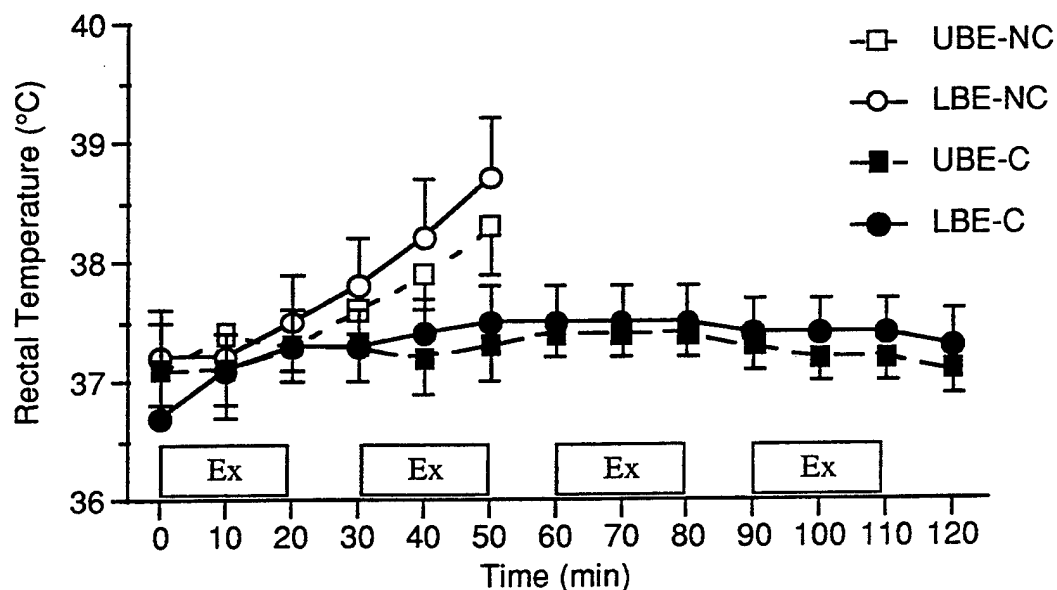

Figure 2. Rectal temperature (mean ± SD) with time. Bouts of exercise are denoted as Ex.

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$\bar{T}_{sk}$ at termination for UBE-NC (37.9 ± 0.3°C) was less than ($p < 0.01$) for LBE-NC (38.8 ± 0.6°C). However, $\bar{T}_{sk}$ was not different between UBE and LBE in either NC or C trials. $\bar{T}_{sk}$ increased over time ($p < 0.001$) in the NC trials, and decreased over time ($p < 0.001$) in the C trials. $\bar{T}_{sk}$ with time is displayed in Figure 3.
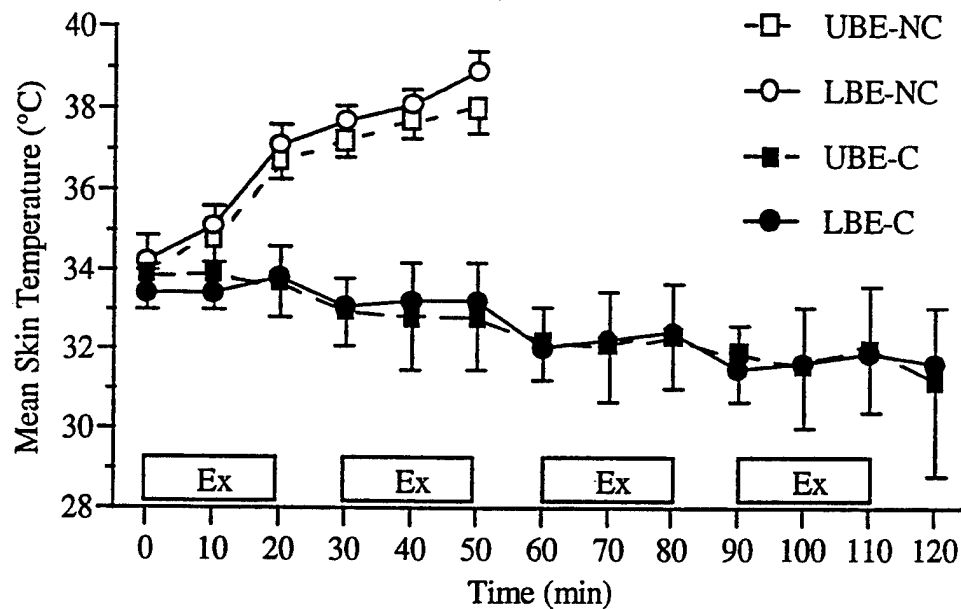

Figure 3. Mean skin temperature (mean ± SD) with time. Bouts of exercise are denoted as Ex.

Cardiopulmonary

HR at termination (UBE-NC = 166 ± 13 beats·min⁻¹ and LBE-NC = 157 ± 15 beats·min⁻¹) was not significantly different between exercise modes when no cooling was provided. Final HR for UBE-C (109 ± 19 beats·min⁻¹) was significantly higher ($p < 0.05$) than that for LBE-C (96 ± 10 beats·min⁻¹). Figure 4 shows the HR response in all four conditions. HR was significantly higher ($p < 0.01$) in the UBE-C than in the LBE-C trials, but HR was not significantly different between UBE-NC and LBE-NC ($p < 0.05$) conditions. In addition, HR increased ($p < 0.001$) over time in the NC but not in the C conditions.
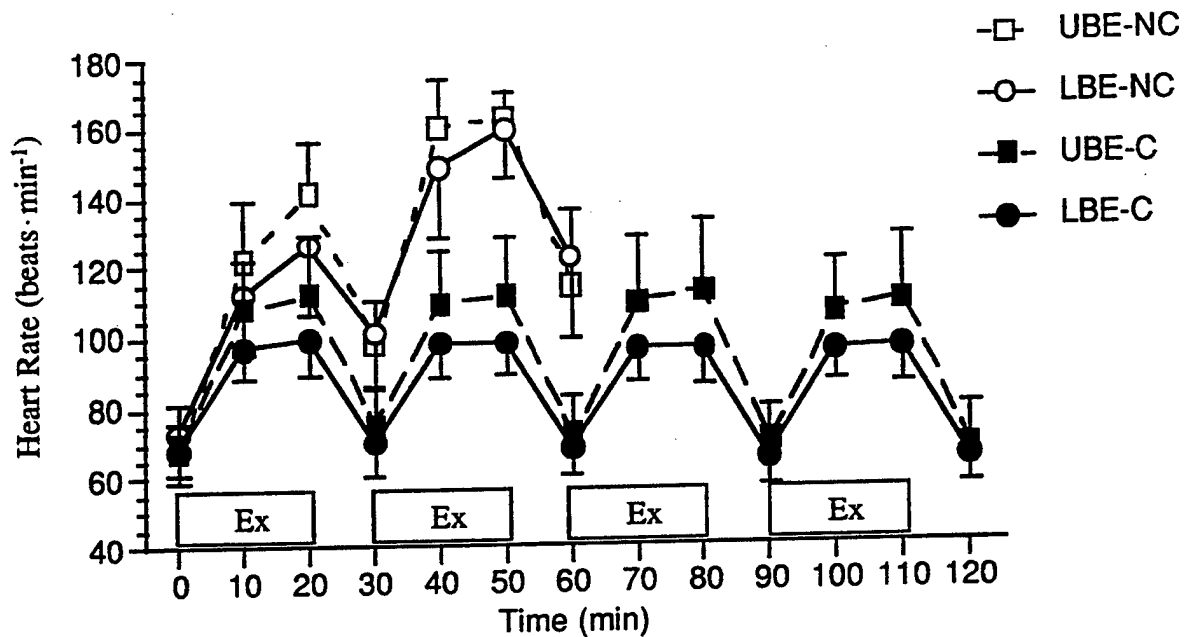
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Figure 4. Heart rate (mean ± SD) with time. Bouts of exercise are denoted as Ex.

Respiratory

As was intended, $\dot{V}O_2$ was not significantly different between the exercise modes and did not increase over time (see Table 3). $\dot{V}_E$ increased over time in the NC trials ($p < 0.01$) but not in the C trials (see Table 4). There were no differences in $\dot{V}_E$ between the modes of exercise in either cooling condition.

Table 3. $\dot{V}O_2$ (mean ± SD) at the end of each exercise bout.

$\dot{V}O_2$ (L·min^{-1})				
Condition	Exercise 1	Exercise 2	Exercise 3	Exercise 4
UBE-NC	1.1 ± 0.2	1.3 ± 0.2	NA	NA
LBE-NC	1.3 ± 0.2	1.3 ± 0.1	NA	NA
UBE-C	1.1 ± 0.3	1.1 ± 0.2	1.1 ± 0.2	1.1 ± 0.2
LBE-C	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1

Table 4. $\dot{V}_E$ (mean ± SD) at the end of each exercise bout.

$\dot{V}_E$ (L·min^{-1})				
Condition	Exercise 1	Exercise 2	Exercise 3	Exercise 4
UBE-NC	25 ± 6	33 ± 5	NA	NA
LBE-NC	26 ± 6	28 ± 3	NA	NA
UBE-C	24 ± 7	23 ± 6	24 ± 5	23 ± 6
LBE-C	23 ± 2	23 ± 2	23 ± 3	23 ± 2

Relative Ratings

RPE was significantly higher ($p < 0.01$) during UBE-NC than during LBE-NC, and it was significantly higher ($p < 0.05$) during UBE-C than during LBE-C (see Table 5). TS was not different between the modes of exercise in either cooling conditions (see Table 6).

Table 5. RPE (mean ± SD) recorded at the end of each exercise bout.

Rating of Perceived Exertion				
Condition	Exercise 1	Exercise 2	Exercise 3	Exercise 4
UBE-NC	11.9 ± 2.2	13.3 ± 2.9	NA	NA
LBE-NC	11.0 ± 1.9	11.9 ± 2.2	NA	NA
UBE-C	10.1 ± 2.7	10.4 ± 2.7	10.5 ± 2.5	11.1 ± 2.5
LBE-C	9.3 ± 2.3	9.1 ± 2.2	9.3 ± 2.3	9.1 ± 2.2

Table 6. Thermal Sensation (mean ± SD) recorded at the end of each exercise bout.

Thermal Sensation				
Condition	Exercise 1	Exercise 2	Exercise 3	Exercise 4
UBE-NC	3.1 ± 0.6	3.5 ± 0.5	NA	NA
LBE-NC	2.8 ± 0.7	3.1 ± 0.8	NA	NA
UBE-C	0.0 ± 1.2	-0.4 ± 0.9	-0.3 ± 0.9	-0.3 ± 0.9
LBE-C	-0.4 ± 1.3	-0.8 ± 1.3	-0.8 ± 1.3	-0.6 ± 1.3

SR was neither different between UBE-NC and LBE-NC, nor between UBE-C and LBE-C. ESR was not different between UBE and LBE (see Table 7).

Table 7. SR and ESR (mean ± SD) for all conditions.

Condition	SR (L·hr^{-1})	ESR (L·hr^{-1})
UBE-NC	1.5 ± 0.4	0.5 ± 0.2
LBE-NC	1.8 ± 0.4	0.6 ± 0.2
UBE-C	0.4 ± 0.2	0.1 ± 0.1
LBE-C	0.3 ± 0.2	0.1 ± 0.1

Heat Transfer

At the end of each exercise bout, $\dot{Q}$ was significantly higher ($p < 0.05$) during LBE-C than during UBE-C; however at the end of each rest period, $\dot{Q}$ was not significantly different between the modes of exercise (see Figure 5).
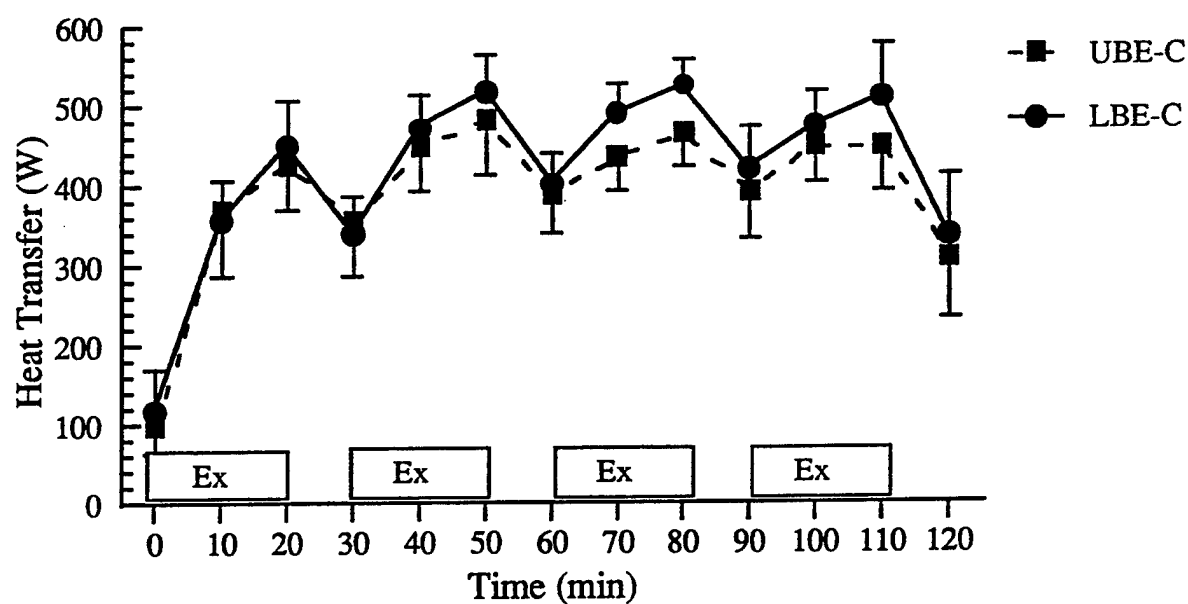

Figure 5. $\dot{Q}$ (mean ± SD) with time. Bouts of exercise are denoted as Ex.

Discussion

This study was designed to determine if thermoregulatory responses to UBE and LBE differ when performed at the same metabolic rate. Since UBE has been shown to be less efficient than LBE, metabolic rate, rather than an absolute PO, was used to provide an equivalent metabolic heat production for arm crank and treadmill exercise. To achieve the target $\dot{V}O_2$ of 1.2 L/min, a PO of 30 ± 2 W was required for LBE. Efficiency of LBE for this study was 8%, which was much lower than the 29% usually attributed to LBE. However, others have found a 5% to 22% decrement in LBE efficiency when CP clothing is worn (Murphy et al., 1993). In this study, UBE was performed at 11% efficiency (41 ± 7 W). Other studies have reported arm crank exercise efficiencies of 13% (Toner et al., 1983) to 24% (Pendergast et al., 1979) when performed in a seated or supine position. However, when UBE is performed in a standing position without body restraints, as was the case in this study, an 11% efficiency has been reported (Louhevaara et al., 1990). Although exercise efficiency and PO differed between LBE and UBE in this study, $\dot{V}O_2$ was not significantly different between the modes of exercise.

In this study, the environmental conditions were 49°C and 20% RH, which is more extreme than in the studies cited. In a hot, arid climate, where ambient temperature is greater than $\bar{T}_{sk}$, heat loss is achieved primarily via sweat evaporation. In the NC condition, the rate of sweat production was high, and as others have reported previously, SR was not different between UBE and LBE trials (Pivarnik et al., 1988; Sawka et al., 1984a; Sawka et al., 1984b). However, the CP clothing used in this study restricted sweat evaporation, thus, only one third of the sweat produced actually evaporated. Therefore, negligible metabolic heat produced or the environmental heat gained was eliminated via evaporative cooling. Hence, heat strain quickly ensued in the NC trials because normal avenues of heat loss were restricted by the environment and by the CP clothing.

In the NC condition, T_{re} and HR, indicators of heat strain, increased over time in both the UBE and LBE tests. We found that T_{re} was not different between UBE and LBE, which is in agreement of others (Pivarnik et al., 1988; Sawka et al., 1984a). In this study, HR in the UBE-NC condition was 12% higher than in the LBE-NC condition. A higher HR during UBE than during LBE has been reported previously; however, the difference was much larger (25%) than was found here (Pivarnik et al., 1988). The larger difference in HR reported by Pivarnik et al. (1988) may have been due to the greater PO required in that study (75W) compared with this study (30W to 40W). The relatively small difference in HR response between UBE-NC and LBE-NC may also be attributed to the extremely hot environment used in this study (49°C). When

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exercise occurs in a hot environment, skin blood flow (SkBF) increases to facilitate heat loss, however, this response decreases SV and necessitates a higher HR to maintain cardiac output. In the case of UBE, SV is lower than during LBE, which may affect SkBF. In this study, final $\bar{T}_{sk}$ was lower following UBE-NC than LBE-NC. This lower $\bar{T}_{sk}$ may be indicative of reduced SkBF in UBE-NC compared with LBE-NC. Hence, a higher SkBF in LBE than in UBE may account for the smaller than expected mode-related difference in HR.

The subjects were able to stay in the extreme environment slightly longer during the LBE-NC (56 ± 13 min) than during the UBE-NC (51 ± 12) tests. The criteria for test termination based on T_{re} or HR were met in four of eight tests for LBE-NC and two of eight tests for UBE-NC. The other tests were primarily terminated by voluntary withdrawal or investigator intervention. The investigator terminated tests if a subject was disoriented, dizzy, or unable to focus on the task. After exiting the chamber, the subjects were asked why they terminated the test, with "difficulty breathing" as the primary reason for early termination. We hypothesize that this sensation is largely due to gas mask use. The lesser tolerance time and the greater prevalence of early withdrawal based on "breathing difficulty" in the UBE trials may be due to a mode-related difference in ventilatory response to exercise. $\dot{V}_E$ is greater during UBE than during LBE when exercise is matched for $\dot{V}O_2$ (Bevegard et al., 1966; Toner et al., 1990). This greater $\dot{V}_E$ appears to be secondary to the greater blood lactate concentration (Davies & Sargeant, 1974; Pimental et al., 1984) and to the associated lower arterial pH found with UBE than with LBE (Sawka et al., 1982). Metabolic acidosis provides a pronounced respiratory stimulus, and this could be problematic when breathing against a resistance.

Respiratory resistance was created by the one-way valve on the gas mask (i.e., inspiratory resistance) and by the 2.5-m hose through which expired air was collected (i.e., expiratory resistance). It has been reported that the dead space created by and the respiratory resistance associated with gas masks leads to respiratory alterations, including an increase in TV, a decrease in f, and a decrease in $\dot{V}_E$ (Bartlett et al., 1972; Flook et al., 1973). These alterations reduce the work of breathing but may result in elevation of the partial pressure of CO_2 (pCO_2) in blood (Flook et al., 1973). Increases in blood pCO_2 can produce dizziness and disorientation. Both CO_2 and hydrogen ions have a stimulatory effect on respiration, and their effects are additive. In this study, $\dot{V}_E$ during the last exercise bout attempted was higher ($p < 0.04$) during UBE (34 ± 4 mL/min) than during LBE (28 ± 3 mL/min), and this difference may account for the greater incidence of test termination due to breathing difficulty.

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Earlier termination in UBE-NC condition may have been due to greater cardiovascular compromise than in LBE-NC. SV during UBE in a warm environment has been shown to decrease as much as 18% in the first 30 min of exercise (Hopman et al., 1993), and reductions in SV may not be adequately compensated by increases in HR. There is some indication that, regardless of HR, a threshold SV must be obtained for exercise to continue in a hot environment (Heaney et al., 1992). Although SV was not measured in this study, symptoms of cardiovascular compromise, such as dizziness, disorientation, and confusion, were evident at test termination. These symptoms were evident in both UBE-NC and LBE-NC, however, they resulted in earlier termination of UBE-NC trials. Therefore, in this extremely hot environment, when normal avenues of heat loss were restricted, mode of exercise affected tolerance time.

The cooling provided was determined by subjects' TS rating. Effort was taken to maintain a subjective TS rating of -1 for each subject. In the C conditions, the TS ratings were between zero and -1 for the duration of the trial. To maintain a -1 TS rating, T_{wi}, which determines the cooling potential in the cooling system, was modulated. Thus, a lower T_{wi} corresponds to a greater $\dot{Q}$. In this study, mean T_{wi} in UBE-C (21.09 ± 2.7°C) and in LBE-C (20.71 ± 2.3°C) conditions was not significantly different between UBE-C and LBE-C, and therefore cooling potential was not different.

The cooling provided in this study proved to be efficacious in reducing heat strain. With cooling, all subjects were able to complete the 2-hr protocol. In addition, cardiac drift was not evident, SR was reduced, and only a slight rise in T_{re} was observed. In agreement with previous findings, no exercise mode-related differences in T_{re}, $\bar{T}_{sk}$, or SR were found, while a higher HR in UBE than in LBE was found (Pivarnik et al., 1988; Sawka et al., 1984a; Sawka et al., 1984b). Hence, with cooling, heat strain appears to be related to metabolic rate and not to the region of muscle mass employed; however, HR is exercise-mode dependent.

During exercise, heat transfer was greater during LBE than during UBE. The greater $\dot{Q}$ may have been due to an exercise mode-related difference in metabolic heat production. Although $\dot{V}O_2$ was only slightly higher for LBE than for UBE (1.2 ± 0.1 L·min⁻¹ vs. 1.1 ± 0.2 L·min⁻¹, respectively), LBE was performed at a lower efficiency than UBE (8% vs. 11%, respectively). These findings suggest that more metabolic heat was produced during LBE than during UBE. Since neither T_{re} nor $\bar{T}_{sk}$ was different between LBE-C and UBE-C, the additional heat produced during LBE was transferred to the cooling system rather than stored in the body. These results differ from a previous study by Toner et al. (1984) who reported lower T_{re} in UBE than in LBE and greater heat loss during UBE than LBE. In the Toner et al. (1984) study,

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subjects performed both UBE and LBE for 45 min while submerged to the neck in 26°C water. Because this represented a slightly hypothermic environment, T_{re} and $\bar{T}_{sk}$ declined during the trials, and SkBF was likely reduced. Toner et al. (1984) suggested that the greater conductive heat loss during UBE than during LBE can be attributed to the larger surface area-to-mass ratio of the arms when compared with the legs. When Toner et al. (1984) performed these tests in water at 33°C, T_{re} was maintained, and $\bar{T}_{sk}$ rose ~4°C. In this environment there was no mode-related difference in heat flow, $\bar{T}_{sk}$, or T_{re}. These findings suggest that when SkBF is reduced, heat loss is related to surface area-to-mass ratio and thus, related to region of muscular activity. However, when SkBF is elevated, whole-body heat transfer appears to be related to metabolic heat production rather than to region of muscular activity.

Conclusions

Indices of heat strain, such as T_{re}, $\bar{T}_{sk}$, and SR, were not different between the UBE and LBE trials in both the NC and C conditions. UBE elicited a greater HR response than LBE, but this difference was reduced in the NC condition. Subjective cooling requirements (i.e., the T_{wi} needed to maintain a −1 TS rating) was not different between UBE and LBE. Heat transfer to the cooling system was slightly greater during LBE than during UBE, possibly due to the lower efficiency in performance of LBE. Under these conditions, heat transfer and heat strain appear to be related to metabolic heat production rather than to region of muscular activity. Thus, safety standards and cooling devices currently used by the military may offer equivalent protection against heat injury when either LBE or UBE is required.

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13. ABSTRACT (Maximum 200 words)

The purpose of this study was to examine the effects of exercise mode on heat strain when cooling was provided by liquid-based microclimate cooling. Eight males exercised 20 min every half hour for a total of 120 min in a hot environment (49°C, 20% relative humidity) while dressed in a chemical protective overgarment. Subjects completed the following four tests: upper body exercise (UBE) with no cooling (NC), UBE with cooling (C), lower body exercise (LBE) with NC, and LBE with C. Work rates were selected to elicit an oxygen uptake of 1.2 L/min. Heart rate (HR), rectal temperature (T_{re}), and whole body sweat rate (SR) were measured as heat strain indicators. Heat strain indices were similar between LBE and UBE when no cooling was provided. When cooling was provided, SR and T_{re} were similar between exercise modes, but HR was significantly higher during UBE-C (109 ± 19 beats·min^{-1}) than during LBE-C (96 ± 10 beats·min^{-1}). Heat transfer to the cooling system was greater during LBE than during UBE, possibly due to the lower efficiency in performance of LBE. Thus, whole body heat transfer under these conditions may be related to metabolic heat production rather than to region of muscular activity.

14. SUBJECT TERMS
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